Theory Aspects of Double-Spin Asymmetries in Proton-Nucleon Collisions

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Abstract

The study of two spin asymmetries in hadron-hadron collisions probes the details of fundamental particle interactions in ways infeasible to machines with unpolarized collisions. Within reach is how the proton spin is distributed among its constituents through ΔG and $\Delta \bar{q}$. Measuring couplings, furthering our understanding jet structure and uncovering new physics are all among the possibilities available at polarized colliders. Spin physics may also deepen our understanding of higher twist behavior and the transition between perturbative and nonperturbative physics. An overview of the double spin physics is presented in this report.

[1]

1   Introduction

The study of two spin asymmetries in hadron-hadron collisions probes the details of fundamental particle interactions in ways infeasible to machines with unpolarized collisions. Within reach is how the proton spin is distributed among its constituents through ΔG and $\Delta \bar{q}$. Measuring couplings, furthering our understanding jet structure and uncovering new physics are all among the possibilities available at polarized colliders. Spin physics may also deepen our understanding of higher twist behavior and the transition between perturbative and nonperturbative physics.

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[1]Talk presented during the Workshop on the *Prospects of Spin Physics at HERA* held at DESY-Zeuthen, Germany, 28-31 August 1995.

In this talk I present an overview on theoretical aspects of double spin asymmetries in proton-nucleon collisions. This is a large topic, and I do not intend to cover all the double spin physics involved with all conceivable machines. For this reason, examples have been selected to demonstrate various ideas, and since the Relativistic Heavy Ion Collider (RHIC) has been approved, most of the examples available tend to be from studies at RHIC energies ($\sqrt{s} = 50 - 500\,\text{GeV}$). For further details, the reader is directed to the proceedings of the many conferences that have been held on spin physics (*e.g.*, [1, 2]) or to the various review articles that appear in the literature[3].

By manipulating the spins of the two initial particles in the collision, we exert a maximum in control over the degrees of freedom within our reach. Nevertheless, we are not required to restrict ourselves to spins solely in the initial state. Double spin asymmetries can also be obtained with one spin in the initial state and one spin in the final state or even with both spins taken from the final state.

Starting with some general comments, we look at spin physics from a density matrix approach and see what asymmetries probe parity violation and what asymmetries probe higher twist effects. Proceeding from the perspective of a factorized cross section, we find that the spin contributions can be isolated into three separate sources: the parton distributions, the hard scatter and the final state fragmentation or decay. We proceed to delve into the details one at a time.

2   General Comments

2.1   Some Double Spin Asymmetries[4,39]

The first two asymmetries we examine are single spin asymmetries. With momentum and longitudinal spin information on only one of the particles in the process, we have

$$A_L = \frac{d\sigma(+) - d\sigma(-)}{d\sigma(+) + d\sigma(-)}, \tag{1}$$

where $d\sigma(+)$ $(d\sigma(-))$ represents the differential cross section for right-handed (left-handed) helicity. In terms of the corresponding helicity amplitudes, $M(+)$ and $M(-)$, this asymmetry has the dependence,

$$A_L \propto [|M(+)|^2 - |M(-)|^2]. \tag{2}$$

Since parity conservation demands $|M(+)|^2 = |M(-)|^2$, a nonzero value for A_L signals parity violation.

With momentum and transverse spin information on only one of the particles in the process, we have

$$A_T = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}, \tag{3}$$

where $d\sigma^{\uparrow}$ ($d\sigma^{\downarrow}$) represents the differential cross section when the particle's spin vector is directed in the upward (downward) transverse direction. As can be seen from density matrix calculations, this asymmetry is proportional to the well known "helicity flip" amplitude:

$$A_T \propto \text{Im}[M(+)M(-)^{\dagger}]. \tag{4}$$

Perturbative QED and QCD yield tree level amplitudes that are real; consequently, $A_T = 0$ is expected at this level. Imaginary amplitudes can appear, however, from loop diagrams and higher twist effects, resulting in nonzero A_T.

Moving on to the double spin asymmetries, we discuss four possibilities:

$$A_{LL} = \frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)}, \qquad A_{LL}^{PV} = \frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)}, \tag{5}$$

$$A_{TT} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}, \qquad A_{TL} = \frac{d\sigma(\uparrow +) - d\sigma(\downarrow +)}{d\sigma(\uparrow +) + d\sigma(\downarrow +)}, \tag{6}$$

where the first (second) index in $d\sigma$ indicates the polarization of the first (second) particle whose spin we are monitoring. In this case, the density matrix tells us the dependence on the helicity amplitudes for the longitudinal asymmetries is

$$A_{LL} \propto [|M(++)|^2 - |M(+-)|^2] \qquad \text{and} \qquad A_{LL}^{PV} \propto [|M(++)|^2 - |M(--)|^2]. \tag{7}$$

As the label indicates, $A_{LL}^{PV} \neq 0$ results from parity violation. For A_{LL}, there is no reason to expect $|M(++)|^2 = |M(+-)|^2$ in QED or QCD, even at tree level. With this nonzero spin combination understood from a perturbative standpoint, we have a useful tool for probing less understood contributions to the cross section, like the parton distribution functions. The asymmetry A_{TT}, like A_{LL}, also gains nonzero values at tree level in QED and QCD due to terms like $\text{Re}[M(++)M(--)^{\dagger}]$. The asymmetry A_{TL} on the other hand, is similar to A_T in that it requires nonzero imaginary portions to the amplitude or higher twist effects to generate nonzero values.

Summarizing, we find that the asymmetries A_{LL} and A_{TT}, with their nonzero values at leading order (LO), can be used as a tool to study the nonperturbative structure in the cross section. The asymmetries A_L and A_{LL}^{PV} are sensitive to parity violation effects, and the asymmetries A_T and A_{TL} are better suited for probing higher twist.

3   Factorization

The factorization of the cross section into perturbative and nonperturbative parts, which we frequently use in our studies of unpolarized collisions, also follows

through for expressing polarized cross sections[5]. In the case of A_{LL}, where the two incoming hadrons are polarized, we have[3]

$$A_{LL} = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_A \, dx_B [\Delta f_{i/A}(x_A, Q) \Delta f_{j/B}(x_B, Q) + (i \leftrightarrow j)] \hat{a}_{LL}^{ij}/d\sigma \quad (8)$$

where Δf is the parton helicity density and $\hat{a}_{LL}^{ij}$ is the parton level asymmetry. We can also consider asymmetries resulting from spin effects in fragmentation. Here, we show the spin dependence in the cross section as reflected by a density matrix factor[6],

$$E_C \frac{d^3\sigma}{d^3p_C} = \sum_{abc} \int dx_A \, dx_B \frac{dz}{z} \qquad \rho_{\alpha\alpha'} f_{a/A}(x_A, Q) f_{b/B}(x_B, Q)$$

$$d\sigma_{\alpha\alpha'\beta\beta'}(a + b \rightarrow c + X) \rho_{\beta\beta'} D_{C/c}(z), \quad (9)$$

where f is the unpolarized parton density, D is the fragmentation function and ρ is the density matrix over helicities $\alpha, \alpha', \beta, \beta'$. Analogous formulas follow for the case of transverse spins[5, 7].

From this perspective, we identify three sources for spin effects:

> $\hat{a}$ the hard scattering asymmetry
>
> $\Delta \mathbf{D}$ the helicity dependent fragmentation functions
>
> $\Delta \mathbf{PDFs}$ the parton helicity distributions

Next, we discuss spin in each of these parts. For details the reader is directed to the appropriate references.

4 Getting the Spin Information

4.1 Accessing Asymmetries in the Hard Scattering

In general, polarization can be used to measure the couplings or form factors that govern the interactions in the hard scattering portion of the cross section.

In Ref. [8] we investigated what can be learned about the couplings for a new scalar or vector boson produced in hadron-hadron colliders with or without polarizing the beams. We studied this from the perspective of a lowest order Drell-Yan calculation within the resonance of the new particle, where interference effects are minimal. We recapitulate some of that discussion here.

We saw that one longitudinally polarized beam permits a study of parity violation in the lowest order Drell-Yan process while with two longitudinally polarized beams spin one bosons may be distinguished from spin zero bosons through helicity conservation. Scattering with longitudinal beams alone, however,

is insufficient for distinguishing between the scalar and the pseudoscalar couplings or between the vector and the axial vector couplings. Given that we know the boson spin, we also do not gain access to any new information on the couplings of the scalar or vector boson when both initial beams are polarized longitudinally as compared to the case when only one beam was longitudinally polarized.

It is only with *two* transversely polarized beams that we were able to distinguish between scalar and pseudoscalar couplings or between vector and axial vector couplings. Furthermore, we found that comparisons where the transverse polarizations of the two colliding hadrons are perpendicular to each other versus parallel or antiparallel provides a probe of the CP invariance of the couplings provided the effects are large enough to be measured. To have only one beam with some transverse polarization gains nothing.

So, Ref. [8] showed, using Drell-Yan production of new bosons as an example, that to make a complete measurement of the couplings for a new physics process requires the use of both transverse and longitudinal polarizations for the hadron beams. If we were to consider a more general process than Drell-Yan, our conclusion would still hold—full polarization information is needed to measure all couplings.

In general, studying the couplings can get more involved than our example. One may wish to examine other interactions besides those considered here which may enter the effective theory, *e.g.*, through a chiral lagrangian approach. Loop corrections can generate chromoelectric or chromomagnetic moments, and if these loops are generated through weak boson exchange, parity violation may be introduced[9, 10].

Specific sources for nonzero values of $\hat{a}$ are often predicted in models that introduce physics beyond the standard model. One example appears in technicolor models[11], where a four-fermion contact term in the interaction lagrangian displays a manifest parity violation in its γ_5 dependence,

$$\mathcal{L}_{4q} \propto \bar{\Psi}\gamma_\mu(1-\eta\gamma_5)\Psi\bar{\Psi}\gamma_\mu(1-\eta\gamma_5)\Psi, \tag{10}$$

where Ψ is a quark doublet and $\eta = 0, \pm 1$. At energies of $\sqrt{s} = 500\,\text{GeV}$ Taxil and Virey compute asymmetries ranging over a -5% to +10% range at high transverse momentum.

Supersymmetry is also replete with parity violating interactions[12]. For example, the pseudoscalar couplings to quarks or neutralinos and the charged higgs boson couplings to quarks carry a different left-handed and right-handed behavior. This manifest parity violation can easily create deviations from the expected asymmetries for ordinary particle production[3].

Taken in the light of what has been reviewed in this discussion, polarization is an essential tool for studying the interactions of new bosons in hadron-hadron colliders.

4.2 Accessing Asymmetries in the final state

As we discussed previously, many asymmetries tend to vanish when we only keep track of one spin in the reaction. With only one spin in the initial state, it falls to the final state to provide us with the second spin to obtain a nonzero asymmetry. To extract this spin information in the final state typically requires interpreting the particle correlations that result from particle decay or fragmentation.

4.2.1 Self-Analyzing Decays

Particle decay is useful for extracting a final state polarization because many particles are "self-analyzing," meaning that the decay distributions reflect the polarization of the parent particle. Among the particles that have been analyzed from this perspective are the τ[13], the Λ and other hyperons[14].

As an example, we can look at some of the theoretical work that has been done regarding polarization in top quark decays. It was shown in Ref. [9] that the polarization of the t (and the $\bar{t}$) can be self–analyzed from the decay $t \rightarrow bW^+ \rightarrow bl^+\nu_l$ ($\bar{t} \rightarrow \bar{b}W^- \rightarrow \bar{b}l^-\bar{\nu}_l$). In the the rest frame of the t ($\bar{t}$) quark, the preferred moving direction of the l^+ (l^-) is along the direction of the boost; *e.g.*, the l^+ likes to follow the boost direction of the right-handed top quark and the l^+ likes to go opposite the boost direction of the left-handed top quark. Because of the correlations, it is possible to distinguish different polarization states of the $t\bar{t}$ pairs by the energy distribution of the leptons l^+ and l^- or from their angular distributions[15, 16, 17].
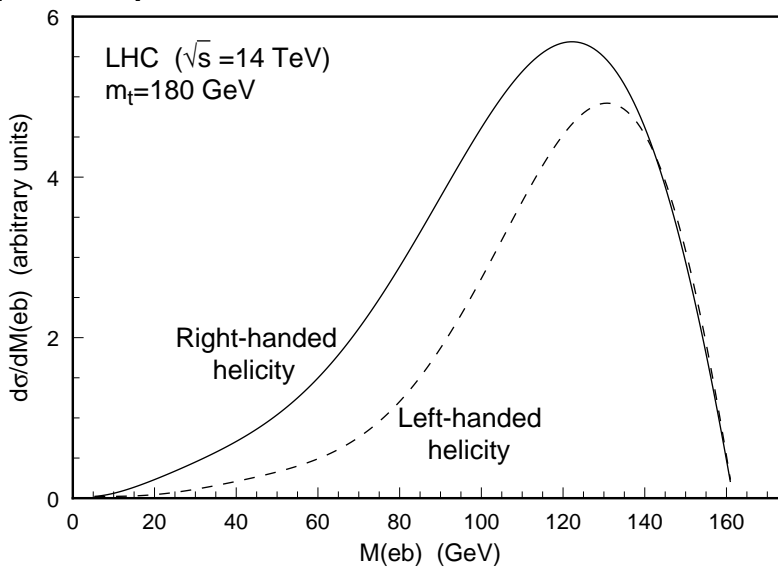

FIG. 1 These two curves represent the distribution $d\sigma/dM(eb)$ vs. $M(eb)$ at the LHC for right–handed and left–handed top quark helicities using $m_t = 180\,\text{GeV}$ and $m_b = 0$. Kinematic constraints in the lab frame on the rapidity ($|\eta| < 2.5$) and transverse momentum ($p_T > 40\,\text{GeV}$) were imposed for the quarks

and visible leptons from the t and $\bar{t}$ decays.

One important issue regarding the reality of analyzing polarization through decay fragments appears when kinematic cuts are imposed on the data. It is often the case that such constraints bias the polarization of the sample. To demonstrate the effect of the spin dependent decay, we plot the $M(eb)$ distribution for $q\bar{q} \to t\bar{t} \to be^+\nu\bar{b}q_1\bar{q}_2$ at the LHC in Fig. 1, separating the contributions for left–handed and right–handed helicities of the top quark. ($M(eb)$ is the mass of the $e^+ + b$ system.) The difference between the two curves shows that it is necessary in experiments and in Monte Carlo studies to keep track of the effect kinematic constraints have with regard to the particle polarizations[18].

4.2.2 Jet Fragmentation

Another analogous means for extracting spin information from final state particles is to analyze the fragmentation products in jets[19, 20]. In the late 1970's, Nachtmann[21] and Efremov[22] proposed looking at vector products of the momenta from selected particles produced in the fragmentation. In Ref. [21], the vector product presented was

$$T \equiv (\mathbf{p}_1 \times \mathbf{p}_2) \cdot \mathbf{p}_3 / |\mathbf{p}|, \tag{11}$$

where $\mathbf{p}$ is the jet momentum and the momenta for the three leading particles in the jet obey $|\mathbf{p}_1| > |\mathbf{p}_2| > |\mathbf{p}_3|$. One can then define the handedness of the jet by collecting the numbers of events where T is positive or negative,

$$H = \frac{N(T < 0) - N(T > 0)}{N(T < 0) + N(T > 0)} = \alpha P, \tag{12}$$

where P is the polarization of the jet and α is the analyzing power we have for seeing the jet polarization. The analyzing power must be measured from experiments. Measurements from the SLD experiment placed upper bounds on the size of the analyzing power after observing results which they conclude are consistent with zero. Recent measurements by the DELPHI collaboration have also found small analyzing powers[23].

A correlated handedness, comparing the simultaneous fragmentation between the two jets in $Z \to q\bar{q}$, has been found by DELPHI of 8.5%. This result is intriguing, not because it is nonzero within errors, but because its sign is opposite from standard model expectations[23].

The fragmentation of transversely polarized quarks[6, 24, 25] will have an azimuthal distribution

$$1 + \alpha \frac{\mathbf{s}_\perp \cdot (\mathbf{t} \times \mathbf{p})}{|\mathbf{p}_\perp|}, \tag{13}$$

where the analyzing power here represents a left-right asymmetry, $\mathbf{s}_\perp$ is the transverse spin vector for the quark, and $\mathbf{p}_\perp$ is the momentum of the observed particle

perpendicular to the jet axis, **t**. Providing that we understand the analyzing powers, we can use jet fragmentation to pull spin information out of final state jets.

4.3   Helicity Distributions and Structure Functions

From Eq. 8, we see that our ability to extract the parton distribution functions depends on how well we understand the hard scattering. For this reason, processes which are understood through perturbative calculations in the standard model are well suited as tools that allow us to probe the helicity dependence of the parton densities.

Helicity amplitudes and asymmetries for $2 \rightarrow 2$ hard scatterings at tree level are prevalent in the literature[3, 26]. Depending upon the subprocess, these parton level asymmetries range from -1 to $+1$, *e.g.*, $q\bar{q}$ annihilation requires quark and antiquark to have opposite helicities, resulting in $\hat{a}_{LL} = -1$. Transverse asymmetries appear as an azimuthal variation in the amplitude.

The question to ask then, is whether we have sufficient sensitivity to the asymmetries to extract the parton densities[27]. From DIS results on protons and neutrons, we have a good understanding of the up and down quark densities, but the best measurements on gluon and sea quark spin densities will come from hadron-hadron collisions.

4.3.1   Inclusive jet production

In inclusive jet production, we have the advantage of a high event rate which makes it easy to distinguish the various possibilities for gluon and sea quark densities. Depending upon the kinematics selected, we can focus on initial states with either gluons or quarks. In Chiappetta, *et al.*[28], leading order A_{LL} asymmetries vary from zero to about 20%, with a good separation between large and negligible ΔG for $p_T < 60\,\mathrm{GeV}$ in pp collisions at $\sqrt{s} = 500\,\mathrm{GeV}$. The asymmetry drops for $\sqrt{s} = 16\,\mathrm{GeV}$ to about 10-15%, yielding a smaller distinction in this case for $p_T < 1\,\mathrm{TeV}$. With new techniques for computing one loop helicity amplitudes[29], we can look forward to next to order (NLO) results in the near future.

Recall, if parity is conserved, A_L from an inclusive jet cross section must vanish. It is by getting spin information on two of the particles (or momenta from more than one particle in the final state) that the nonzero A_{LL} survives for a parity conserving theory. There has been a recent rise in the output of theoretical work investigating the potential of extracting spin information from a final state jet. If the analyzing powers prove to be large enough, then it is reasonable to see how we might gain information from double spin asymmetries involving one initial state spin and one final state spin. This question was approached by Stratmann and Vogelsang[30], where the asymmetries A_{LL}^{if} and A_{TT}^{if} were computed at the

parton level for inclusive jet production. At $\sqrt{s} = 100\,\mathrm{GeV}$, they find significant variation in the cross section due to ΔG and Δs variations for $p_T < 15\,\mathrm{GeV}$.

4.3.2 Direct photon production

Just as direct photon production has been useful in determining the unpolarized gluon density[31], direct photon production in polarized processes should be useful for determining ΔG. By measuring both the photon and jet from $qg \to q\gamma$, the RHIC should be able to establish the x dependence in $\Delta G(x)/G(x)$. Higher order corrections have been computed for direct photon production in polarized hadron collisions[32]. Contogouris, *et al.*, compute A_{LL} for $\sqrt{s} = 38, 100, 500\,\mathrm{GeV}$; it is at the higher rapidities and transverse momenta where they find the largest variations in the asymmetry due to different ΔG and $\Delta\bar{q}$, and it is also here that the K-factors are largest. The asymmetries get sizable, up to 60% at high transverse momentum.

4.3.3 QCD-Electroweak Interference

Jet production, even though dominated by QCD processes, may carry a parity violating behavior due to the electroweak production mechanisms and their interference with QCD processes[11, 33]. This parity violation can appear both in A_L and A_{LL}^{PV}. Without cuts, Refs. [11, 33] demonstrate asymmetries around the percent level for pp and $p\bar{p}$ collisions ranging from $\sqrt{s} = 250 - 850\,\mathrm{GeV}$. Variations in A_{LL}^{PV} due to PDF uncertainties have been demonstrated in Ref. [11] to get as large as 0.01, but at large transverse momentum; with high luminosities, the RHIC should be able to distinguish between extreme variations caused by varying the PDF.

4.3.4 Heavy Quark Production

As with unpolarized parton distribution functions[34], it is expected that open heavy flavor production provides an optional probe of the gluon spin density. Studies of heavy flavor production in polarized collisions have been performed at LO[35] and NLO[36]. At leading order, large values of $\hat{a}_{LL}$ may be obtained, near -1 at large transverse momenta. In Ref. [36], however, sizable cancellations were found between the LO and NLO contributions in the spin dependent production of heavy quarks, leading to the conclusion that a reliable extraction of polarized parton densities in hadron collisions may be more dependent on radiative corrections than has been observed with unpolarized parton densities.

4.3.5 The Drell-Yan Process, Sea Quarks and Electroweak Boson Production

The cross section for the production of $\mu^-\mu^+$ pairs of mass M in the parton model is[3]

$$\frac{M^3 d^2\sigma}{dMdx_F} = \frac{8\pi\alpha^2}{9}\frac{x_1 x_2}{x_1 + x_2}\sum_a e_a^2[f_{a/A}(x_1)f_{\bar{a}/A}(x_2) + (1 \leftrightarrow 2)] \qquad (14)$$

making the Drell-Yan mechanism a prime probe of the sea quark distributions. The resultant asymmetry is directly proportional to the polarized sea quark density,

$$A_{LL} \propto \frac{\sum_a e_a^2[\Delta f_{a/A}(x_1)\Delta f_{\bar{a}/B}(x_2) + (1 \leftrightarrow 2)]}{\sum_a e_a^2[f_{a/A}(x_1)f_{\bar{a}/B}(x_2) + (1 \leftrightarrow 2)]}. \qquad (15)$$

An electroweak interference can also appear between the photon and Z boson. This has been studied at RHIC energies by Leader and Sridhar[37]. Whether the variations in A_{LL} due to changes ΔG and Δs will be useful depends upon the event rates at the machine of interest.[27]

Armed with an understanding of the unpolarized valence quark densities, electroweak boson production will provide an important test of the flavor breaking of the sea quark distributions[38, 39]. With their parity violating interations, the asymmetries in the production of $W^\pm$ and Z bosons can generate significant values of A_{LL}^{PV}. Bourrely and Soffer[38] show that in $pp \to W^\pm + X$ for RHIC energies we can achieve asymmetries around 50% with a large difference appearing in the asymmetry for $pp \to W^- + X$ if $\Delta\bar{u}$ vanishes.

4.3.6 Drell-Yan and Transverse Spin

The transverse spin of partons in the proton is unmeasurable in the case of deep inelastic scattering[40], and due to helicity arguments, the transversity distribution for the gluons in the proton is zero[7]. Nonetheless, with both incoming hadrons carrying transverse polarization, the Drell-Yan process is useful for studying the transversity distributions of valence and sea quarks[40]. Recall, by separating the azimuthal dependence of the cross into quadrants, an asymmetry in the cross section is obtained,

$$\frac{d\Delta\sigma}{dQ^2 dy d\Omega} = \frac{4\alpha^2 e^2}{9Q^2 s}h_T^A(x_A)\bar{h}_T^B(x_B) + (A \leftrightarrow B), \qquad (16)$$

where h_T and $\bar{h}_T$ are distributions that measure the leading twist transverse polarization. A study of the Drell-Yan cross section, with either photon or Z boson intermediates, would complement an inclusive jet study.

4.3.7 Drell-Yan and Higher Twist

One longitudinal beam against one transverse beam accesses higher twist in $pp \rightarrow \mu^- \mu^+ + X$. Maintaining the intrinsic transverse momentum dependence, Mulders and Tangermann[41] find the asymmetry is

$$A_{LT} = \frac{\sin 2\theta \cos \phi}{1 + \cos^2 \theta} \frac{\bar{U}_{2,1}^{LT}}{\bar{W}_T}, \tag{17}$$

where $\bar{W}_T = \frac{1}{3} \sum_a e_a^2 [f_{q/A}(x_1) f_{\bar{q}/A}(x_2)]$ and the higher twist contribution is contained in $\bar{U}_{2,1}^{LT}$. Experimental results are needed to understand the size of this asymmetry beyond a model dependence.

4.3.8 Miscellaneous

It should go without saying that there are a plethora of processes[26] that have nonzero double spin asymmetries, many of which have been examined theoretically. Among them are the production of 3-jets[42], 4-jets[43], two photons[44], J/Psi[45], etc. These processes have a variety of uses, but they usually take a back seat to the processes with higher event rates and larger asymmetries. These processes are useful for checking the more precise methods of determining ΔG and $\Delta \bar{q}$.

We can also look forward to getting the one loop helicity amplitudes to many processes through the techniques developed from sting theory[29].

5 Conclusions

We have seen how the spin dependence of hadronic interactions can be induced through the spin dependence of the parton distribution function, the hard scatter, or the final state decay and fragmentation. Double spin asymmetries in proton-nucleon collisions will fill and important gap in our knowledge of how the proton spin is distributed among its constituents by providing ΔG and $\Delta \bar{q}$. These asymmetries also can provide an excellent means for understanding fundamental interactions and facilitate studies of new physics. Spin physics will pave the way to further our understanding of higher twist and the transition between the perturbative and the nonperturbative physics. We may also have some surprises unfold as we investigate variables that measure correlations in jet fragmentation.

Acknowledgments

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